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Author(s): D. Vieira, CST-11
E. Chamberlin, CST-11
D. Preston, California State University
V. Sandberg, P-25
D. Tupa, P-25
C. Wieman, University of Colorado/JILA
J. Wouters, CIC-2
G. Butler, P-23
Y. Bai, Utah State University
R. Guckert, University of Glessen

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**Development of Radioactive Beams at LAMPF
for a High Precision Test of the Standard Model
and as a Step Towards an IsoSpin Laboratory**

D. Vieira*, E. Chamberlin, D. Preston (Cal. St. Univ.), V. Sandberg,
D. Tupa, C. Wieman (Univ. of Col./JILA), J. Wouters, G. Butler,
Y. Bai (Utah St. Univ.), and R. Guckert (Univ. of Giessen)

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Producing high yields of isotopically pure beams of radioactive heavy ions is the technical challenge facing the IsoSpin Laboratory (ISL). The main objective of this project is to design, fabricate, install, and make operational a thin-target, He-jet system at LAMPF to provide high-intensity $^{125-139}\text{Cs}$ isotopes for an atomic parity nonconservation (PNC) experiment and as a robust production source for radioactive beams. The Cs-PNC experiment itself would take several years beyond the successful completion of the developments outlined in this project. The experiment seeks to measure the 6S-7S PNC transition rate for this series of Cs isotopes. From the ratios of these rates measured in the different isotopes, a fundamental test of the standard model can be made at the level of 0.2%. Herein, we describe the successful operation of a thin-target, He-jet system operating at primary beam intensities of up to 700 μA with production yields of 10^7 to 10^8 atoms/s for a wide range of nonvolatile and Cs radioisotopes.

1. Background and Research Objectives

Parity Nonconservation in Atomic Systems

The parity nonconserving (PNC) 6S-7S transition rate in stable cesium (^{133}Cs) has been measured by a group from the University of Colorado to an accuracy of 2% [1]. When combined with atomic matrix element calculations (recently improved to an accuracy

*Principal investigator, e-mail: vieira@lanl.gov

of 1% [2]), this information leads to a fundamental test of the standard model of electroweak interactions. Expressed in terms of the weak coupling constant, $\sin^2(\theta_w)$, this work provides a 2.5% measurement of this constant that arises from Z^0 - γ interference at very low momentum transfer. This result is to be contrasted with the $\sim 0.15\%$ accuracy measurement of $\sin^2(\theta_w)$ as deduced from the mass of the Z^0 assuming $m_{\text{top}} = m_{\text{Higgs}} = 100$ GeV [3]. So if the atomic PNC measurements could be improved to match this level of accuracy (at say 0.2%), then the comparison of this PNC data with the Z^0 data would provide a precision test of the standard model.

An improved atomic PNC measurement of stable Cs that has four times better signal-to-noise than the previous experiment and which promises to reach a final experimental uncertainty of 0.5% is now in progress at the University of Colorado. However, the limiting uncertainty of this new measurement is not expected to be the experiment, but rather the uncertainty of the atomic matrix element calculations. Although it is possible and likely that these calculations can be improved, it is not clear when or how the accuracy of the calculations will be verified at the 10^{-3} level. In this work, this limitation would be reduced by taking a ratio of several Cs isotopes such that the effect of the atomic matrix element uncertainties effectively drops out. As recently reviewed by leading authorities in this field [3], it is exactly this experiment which is touted as being one of the four most important experiments that can be done to further test the standard model.

Thus, the main goal of this work is to explore and develop the technology necessary to undertake a multi-isotope Cs PNC experiment at the 0.2% level. This can be achieved through the development and operation of a thin target, He-jet system in the main beam stop and staging areas at LAMPF to provide a reliable production on the order of 10^8 atoms/s for each of the radioisotopes $^{125-139}\text{Cs}$ that are of interest in the experiment. Our University of Colorado collaborators developed the trapping and cooling techniques needed for the measurement. We have recently imported these techniques to Los Alamos with the setup and operation of our first magneto-optical trap (MOT). Future work at Los Alamos involves coupling our MOT to a mass separator and determining how to measure the 6S-7S transition rate in an atom trap at the University of Colorado.

The IsoSpin Laboratory

Besides the value of the thin target, He-jet system science and technology for the atomic PNC experiment, the technology would also be of high value to a radioactive beam facility. The low-energy nuclear science community in North America is developing a proposal to build a facility, called the IsoSpin Laboratory (ISL), that can produce a broad range of β -decay

unstable heavy ion beams with high beam intensities (up to 10^{11} particles/s), state-of-the-art beam purity and emittance, and variable energy up to ~ 20 MeV/u. Given the ISL benchmark design which consists of an on-line mass separator - linear-accelerator post-accelerator system located at a high-intensity medium-energy proton accelerator [4], LAMPF is considered a prime candidate site for an ISL. By taking active steps to develop the front end of the ISL, i.e. the thin target, He-jet system supported by this project, we are also undertaking important R&D directly relevant to enabling an ISL. Thus a second goal of this project is to develop a robust production method as the first step in developing an ISL-type, radioactive beam initiative at Los Alamos.

2. Importance to LANL's Science and Technology Base and National R&D Needs

Successful development of a robust source of radioactive Cs isotopes at LAMPF will lead to measurements of atomic parity nonconservation for a range of Cs isotopes. The results from such measurements will permit a precision test of the standard model that is comparable to the measurements of the Z^0 mass. This is a high priority measurement in the field of nuclear and particle physics. The Cs-PNC experiment is very complex. Only a large multi-discipline laboratory, such as Los Alamos, could undertake this challenging experiment which draws upon our expertise in accelerators, the production and handling of intense sources of short-lived radioactivity, ion source and mass separation technology, and the latest in laser atom manipulation and atomic physics measurement methods. Moreover, this project will also lay crucial ground work for the North American ISL initiative and strongly position LAMPF/LANSCE to be the site of the IsoSpin Laboratory.

The concrete demonstration of high-intensity production sources is very important to the ISL initiative, which has recently been recommended [5] as the most important, new facility for the field of nuclear science. Finally, the development of an optical trap coupled to a mass separator (or mass spectrometer) may have technology transfer or CRADA potential as a new environmental monitoring system for trace amounts of long-lived radioactive species that are hard to detect from their natural radioactive decay signature.

3. Scientific Approach and Results

The Cs-PNC experiment (see Fig. 1) begins with the production of radioactive Cs isotopes in a thin target (typically $\sim 20 \text{ mg/cm}^2$ of depleted uranium) via proton-induced fission or spallation reactions using the high-intensity, 800-MeV proton beam at the LAMPF beam stop. The reaction products recoil out of the target and are thermalized and transported by He gas to a skimmer where the He is largely removed and subsequently recirculated. The reaction products are introduced into an ion source, extracted, accelerated, and mass separated. For the PNC experiment the mass-separated beam would be accumulated on a thin foil. Periodically the collected Cs would be vaporized as atoms and then trapped and cooled in a magneto-optical trap [6]. Once trapped the Cs cloud of $\sim 10^8$ atoms is transferred [7] using optical and magnetic forces into another trap where the transition rate of the 6S-7S forbidden transition rate is measured. With beam intensities of 10^8 atoms/s for Cs isotopes with half-lives of two minutes or longer (i.e. ^{125}Cs to ^{139}Cs), we expect to achieve an experimental uncertainty in $\sin^2(\theta_w)$ of 2 parts in 10^3 .

During the course of the project we have made exceptionally good progress in: (1) completing the fabrication of the He-jet system; (2) installing the He-jet in the main beam stop region of the LAMPF accelerator and; (3) testing and optimizing the operation of the He-jet system with proton beam intensities of up to $700 \mu\text{A}$. The He-jet system consists of a water-cooled, thin-target (depleted uranium), He-jet chamber (see Fig. 2) which is placed in the beam stop region and which is connected via one or more capillary tubes to a helium gas recirculation and Ge gamma-ray detection system located some 30 m away. Our findings indicate that with our new target chamber design the He-jet yields scaled-up linearly with beam intensity from 10 to $700 \mu\text{A}$ with no evidence of heat-driven turbulence effects. Overall He-jet transport and collection efficiencies varied from 15 to 25% depending on He target pressure, flow rates, and aerosols conditions. We consider these efficiencies to be quite reasonable given the He-jet performance values reported by the Chalk River group using heavy ion beams of $1 \mu\text{A}$ or less. From our preliminary analysis the production rates for several of the Cs isotopes of interest in the PNC experiment ranged from 10^7 to 10^8 atoms/s, which satisfies our minimum requirements for the PNC experiment. A more detailed analysis of our results is currently in progress. The He-jet system performed reliably, producing high yields of Cs and other radioisotopes which were more than a 100 times more intense than any previous He-jet system.

In keeping with the recommendations of the IsoSpin Laboratory (ISL) white paper on Research Opportunities with Radioactive Nuclear Beams [5], we have investigated the thin-target / He-jet approach, in part, as an environmentally safe alternative to the standard thick-target approach. As the thick-target method works best for volatile species that rapidly diffuse

out of the target matrix, the thin-target / He-jet method is expected to excel for short-lived non-volatile species. As such, these methods represent complementary production sources for which high-intensity demonstrations have been strongly encouraged by the radioactive beam community. The He-jet tests that we have just completed represent the first successful high-intensity demonstration of the thin-target technology.

As a second step toward undertaking the high-priority Cs-PNC experiment, we have recently built up our own high-intensity magneto-optical trap at Los Alamos. Using a 2-W Ti:Sapphire laser, we have trapped more than 4×10^{10} atoms of stable Cs (see Fig. 3). We are currently working on improving our trapping efficiency by coating our glass trapping cell with a special non-stick coating and by using two-frequency trapping light. Extensive effort has also gone into upgrading one of our existing mass separators to accommodate a MOT. Our near term goal is to demonstrate the trapping of radioactive ^{135}Cs on the mass-separator-coupled MOT by the end of 1995. Beyond the direct significance of this achievement to the Cs-PNC experiment, an important spin-off of this R&D is the development of a mass-separator-coupled MOT as a new analytical tool for the ultra-sensitive detection of extremely small quantities of long-lived radioactive species with applications to nonproliferation and national security.

References:

- [1] M. C. Noecker, B. P. Masterson, and C. E. Wieman, *Phys. Rev. Lett.* **61**, 310 (1988).
- [2] S. A. Blundell, W. R. Johnson, and J. Sapirstein, *Phys. Rev. Lett.* **65**, 1411 (1990).
- [3] P. Langacher, M.-X. Luo, and A. K. Mann, *Rev. Mod. Phys.* **64**, 87 (1992).
- [4] "The IsoSpin Laboratory - Research Opportunities with Radioactive Nuclear Beams", the North American Steering Committee for ISL, R. E. Casten, Chairman, Los Alamos Report LALP 91-51 (Oct. 1991).
- [5] "Long Range Plan for Nuclear Science", DOE/NSF Nuclear Science Advisory Committee, Interim Report, April 1995.
- [6] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, *Phys. Rev. Lett.* **59**, 2631 (1987); C. Monroe, W. Swann, H. Robinson, and C. Wieman, *Phys. Rev. Lett.* **65**, 1571 (1990).
- [7] E. A. Cornell, C. Monroe, and C. Wieman, *Phys. Rev. Lett.* **67**, 2439 (1991).

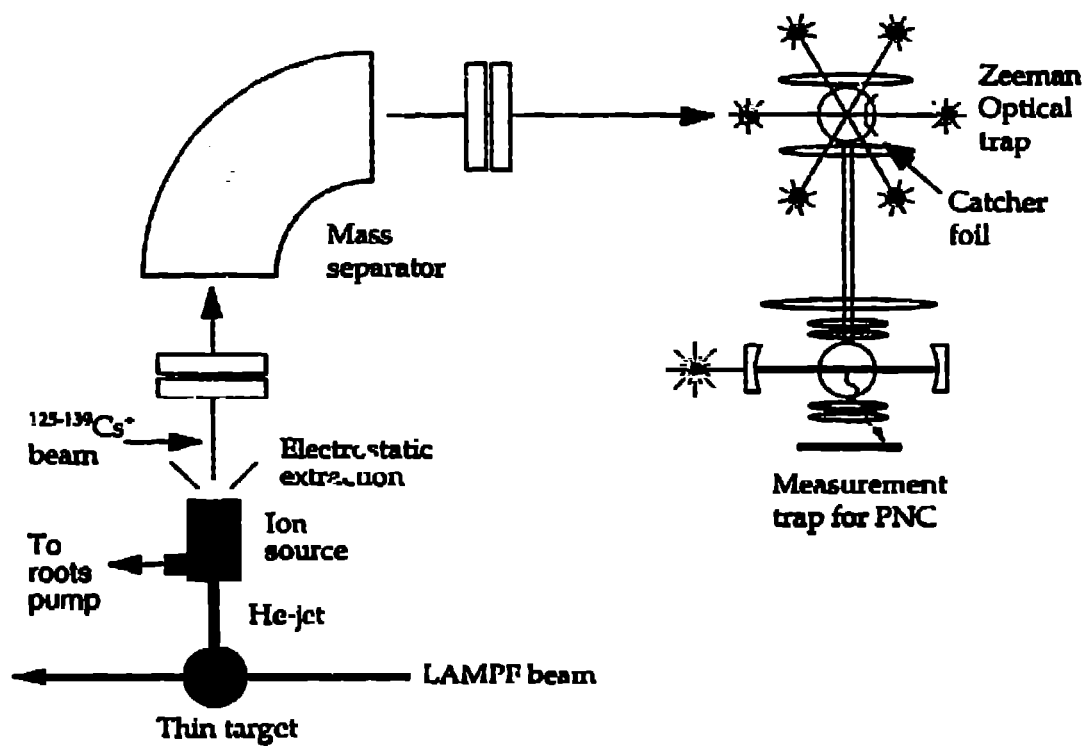


Fig. 1. Overview of the Cs-PNC experiment.

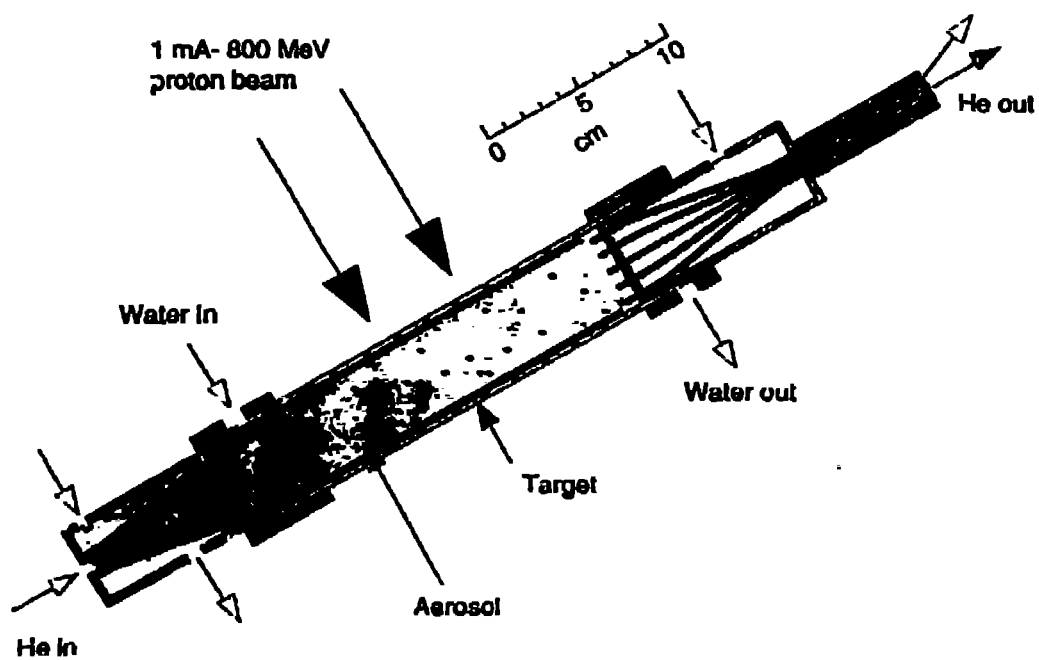


Fig. 2. Schematic of the He-jet target chamber.

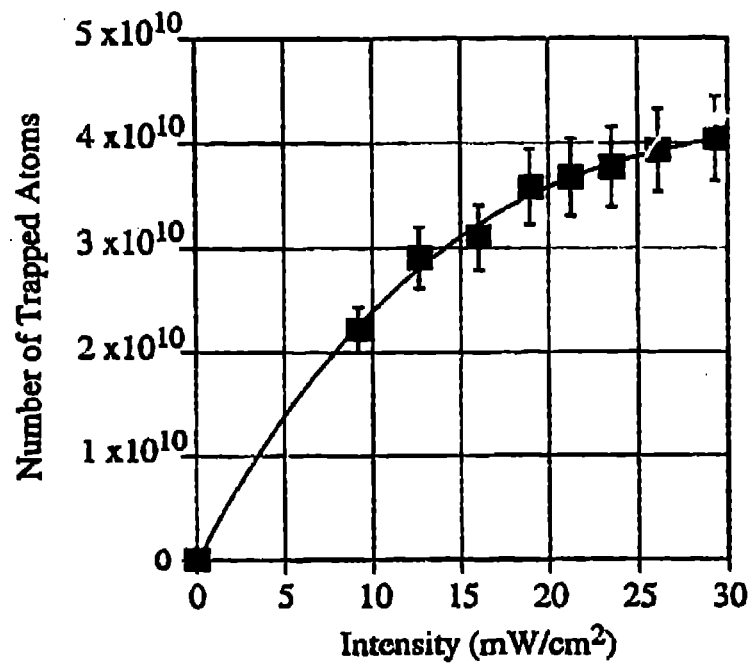


Fig. 3. High-Intensity trapping of stable cesium atoms using a magneto-optical trap. The number of trapped atoms is shown as a function of laser intensity using 4-cm diameter beams and a red-detuning of 20 MHz from the $6S_{1/2} - 6P_{3/2}$ cycling transition at 852 nm.